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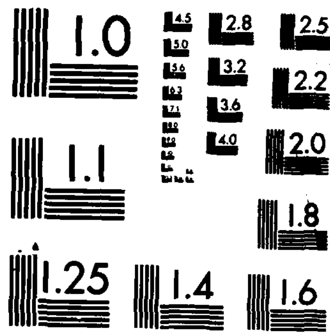

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DYNAMIC CHARACTERISTICS OF THE
48-INCH WATER TUNNEL DRIVE PUMP

K. Ravindra

Technical Memorandum
File No. TM 85-149
26 August 1985
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In this report, the dynamic characteristics of the 48-inch water tunnel drive pump are determined using the theory of unsteady flow around a two-dimensional cascade of airfoils developed by Ohashi [1]. This analysis assumes that the axial surge velocity is uniform across the face of the impeller.

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From: K. Ravindra

Subject: Dynamic Characteristics of the 48-Inch Water Tunnel Drive Pump

References: See p. 9

Abstract: In this report, the dynamic characteristics of the 48-inch water tunnel drive pump are determined using the theory of unsteady flow around a two-dimensional cascade of airfoils developed by Ohashi [1]. This analysis assumes that the axial surge velocity is uniform across the face of the impeller.

It is found that the magnitude plot of the dynamic characteristics is similar to that of a simple control lag element whereas the phase plot looks quite different. The solidity of the rotor in the present analysis need not be large as assumed in previous investigations.

Acknowledgment: This work was performed as part of the E/F Project 6171 entitled, "Experimental and Analytical Study of Nonsteady Forces on Supercavitating Hydrofoils."

Nomenclature

C	Coupling function, Eq. (2)
F	Gauss's hypergeometric function, Eq. (3)
H	Dynamic transfer function
$\bar{H}$	Normalized dynamic transfer function
N_R	Number of blades on rotor
V_{a_0}	Steady axial velocity
Q_0	Steady volume flow rate through the pump

---

i	-1
f	Frequency of fluctuations, Hz
n	Rotational speed of turbopump
t	Time
u	Velocity of the rotor cascade

Δp_R	Unsteady pressure rise through the rotor
Δp_S	Unsteady pressure rise through the stator
ΔV_a	Amplitude of axial velocity fluctuations

ρ	Density of the liquid
λ_R	Stagger angle of rotor
σ_R	Solidity of rotor = chord of blade/spacing of blades
ω_R	Reduced frequency = $f \cos \lambda_R / N_R \phi n$
ν	Frequency of fluctuations, radians/sec
ϕ	Flow coefficient = V_{a_0}/n
Γ	Gamma function

Introduction

Nonsteady cavity flow tests conducted in a closed circuit water tunnel are thought to induce pressure surges in the tunnel circuit thus invalidating the test results [2]. There has been sufficient interest generated [2,4,5] to warrant understanding and analyzing the water tunnel circuit as a dynamic system. Indeed, although many investigators have observed and mentioned the existence of pressure surges in closed circuit water tunnels [2,4,5], there appears to be no systematic study that has been performed to understand the possible existence of pressure surges and to quantify the surge phenomenon (if it exists) so a correction procedure can be adopted for nonsteady cavity flow test data obtained from closed circuit water tunnel tests.

The components of the water tunnel circuit that affect the dynamic behavior of the tunnel circuit have been identified [3] as:

(i) Unsteady cavity motion in the test section.

(ii) Phase shift in the unsteady disturbance due to the tunnel circuit.

(iii) The dynamic characteristics of the tunnel drive pump.

(iv) The pressure control loop involving the differential pressure transducer at the test section, the pressure regulating tank and the controllers.

In this memorandum, the dynamic characteristics of the 48-inch water tunnel drive pump are determined using the theory of unsteady flow around a two-dimensional, linear cascade of airfoils developed by Ohashi [1]. The results obtained show some interesting features that could be important in the dynamic analysis of the water tunnel circuit.

Description of the Tunnel Drive Pump

The axial flow pump of the 48-inch water tunnel at the Garfield Thomas Water Tunnel consists of a four bladed impeller 95 inches in diameter with flow straightening vanes ahead of and behind the impeller. The impeller is driven by a variable speed motor. The speed can be varied continuously from 0 to 180 rpm. The blades of the impeller may be adjusted over approximately 28 degrees [6]. The solidity of the impeller is about 1.0.

Analysis

The relationship between the pressure rise across the pump and the flow rate is indicated by the characteristic curve of the pump. This characteristic curve is valid only when the pump operates in the steady state condition, that is, with a constant flow rate. When the flow rate fluctuates, the pressure rise will not respond fast enough to follow along the steady state characteristic curve.

The dynamic characteristics describe a relation between the fluctuating volume flow rate at the inlet to the pump and the fluctuating pressure rise across the pump, as a function of the frequency of fluctuations. Both amplitude and phase relations have to be obtained for a meaningful use of the dynamic characteristics.

It is assumed that [1]

(i) The flow is a two-dimensional cascade flow for each blade element and it is inviscid, incompressible and non-cavitating.

(ii) The angular momentum of the inlet flow into the rotor is steady.

(iii) The unsteadiness is periodic.

(iv) The increase of velocity head at the outlet edge of the rotor is converted into pressure rise in the following stator or diffuser without any time delay.

The unsteady pressure rise through the rotor and stator is given by [1],

$$\frac{\Delta p_R + \Delta p_S}{\rho} = - u \, \Delta V_a \, \frac{\tan \lambda_R \left[1 - \exp(- \pi\sigma_R)\right]}{1 + i\omega_R \, C(\omega_R, \sigma_R)} \, e^{i\nu t} \quad , \qquad (1)$$

where

Δp_R = Unsteady pressure rise through the rotor

Δp_S = Unsteady pressure rise through the stator

ρ = Density of the liquid

u = Velocity of the rotor cascade

ΔV_a = Amplitude of axial velocity fluctuations

λ_R = Stagger angle of rotor

σ_R = Solidity of rotor = chord of blade/spacing of blades

ω_R = Reduced frequency = $f \cos \lambda_R / N_R \, \phi \, n$

f = Frequency of fluctuations, Hz

ν = $2\pi f$ = Frequency of fluctuations, radians/sec

t = time

i = $- 1$

n = Rotational speed of turbopump

N_R = Number of blades on rotor

ϕ = Flow coefficient = V_{a_0} / n

V_{a_0} = Steady axial velocity .

And $C(\omega_R,\sigma_R)$ the coupling function given by [1] is

$$C(\omega_R,\sigma_R) = -\frac{i}{\omega_R}\left[\pi \frac{\Gamma(1 + i\omega_R)}{\Gamma(\frac{1}{2} + i\omega_R)} - 1\right] + \frac{\pi\,\Gamma(i\omega_R)}{\Gamma(\frac{1}{2} + i\omega_R)}\left[F(-\tfrac{1}{2}, i\omega_R; \tfrac{1}{2} + i\omega_R ;\right.$$

$$\left.\exp(-2\pi\sigma_R)) - 1\right] , \tag{2}$$

where Γ = Gamma function and $F(a,b,c,z)$ is the Gauss's hypergeometric function given by

$$F(a,b,c,z) = \sum_{n=0}^{\infty} \frac{(a)_n (b)_n}{(c)_n n!} z^n \quad , \quad c \neq 0,-1,-2,\ldots \quad . \tag{3}$$

where

$$(a)_n = \frac{\Gamma(a + n)}{\Gamma(a)} \tag{4}$$

$$(b)_n = \frac{\Gamma(b + n)}{\Gamma(b)} \tag{5}$$

$$(c)_n = \frac{\Gamma(c + n)}{\Gamma(c)} \quad . \tag{6}$$

The dimensionless form of unsteady pressure rise is given by

$$h_{R+S} = \frac{\Delta p_R + \Delta p_S}{1/2\rho u^2} = \frac{-2\tan\lambda_R\left[1 - \exp(-\pi\sigma_R)\right]}{1 + i\omega_R\, C(\omega_R,\sigma_R)} \frac{\Delta Q}{Q_0}\, \phi\, e^{i\nu t} \quad , \tag{7}$$

where

ΔQ_0 = Amplitude of unsteady volume flow rate through the pump

Q_0 = Steady volume flow rate through the pump

The dynamic transfer function $H(\omega)$ is therefore given by

$$H(\omega) = \frac{h_{R+S}(t)}{\left(\Delta Q(t)/Q_0\right)} = \frac{-2 \tan \lambda_R\left[1 - \exp\left(-\pi\sigma_R\right)\right]}{1 + i\omega_R\, C\left(\omega_R, \sigma_R\right)}\,\phi \quad , \tag{8}$$

where $\Delta Q(t) = \Delta Q_0 e^{i\nu t}$. When there are no fluctuations in volume flow rate, the quasi steady limit is given by

$$\left(h_{R+S}\right)_{qS} = -2 \tan \lambda_R\left(1 - \exp(-\pi\sigma_R)\right)\frac{\Delta Q_0}{Q_0}\,\phi \exp\left(i\nu t\right) \quad . \tag{9}$$

We may now form the ratio,

$$\bar{H}(\omega) = \frac{h_{R+S}}{\left(h_{R+S}\right)_{qS}} = \frac{1}{1 + i\omega_R\, C(\omega_R, \sigma_R)} \quad . \tag{10}$$

Evaluation of the coupling function $C(\omega_R, \sigma_R)$ requires the use of Gamma function with complex argument. A series expansion [7] given by

$$\Gamma(z) = e^{-z} z^{z-1/2} (2\pi)^{1/2}\left[1 + \frac{1}{12z} + \frac{1}{288z^2} - \frac{139}{51840z^3} - \frac{571}{2488320z^4} + \frac{163879}{209018880z^5} + \frac{5246819}{75246796800z^6} - \frac{534703531}{902961561600z^7}\right] \quad , \tag{11}$$

is made use of in evaluating the hypergeometric function F.

Results and Discussion

The ratio in Eq. (10) which does not contain the simplifications of Ref. [1] is evaluated using the series expansion for $\Gamma(z)$. The result is plotted as a function of frequency ω_R in Fig. 1. The amplitude plot, viz., $20 \log\left(h/h_{qS}\right)$ is flat up to the break frequency and then falls off at approximately 3 dB per octave. Up to about the break frequency, the relation between the flow rate and pressure rise can be expressed by the usual steady state characteristic curve. On the other hand, at frequencies above $\omega_R = 70$, the fluctuation of pressure rise is negligible even though the flow rate fluctuates periodically. An observation of the magnitude plot reveals that it is similar in shape to that of a first order control lag element $\left(\text{of the form } K/(\tau s + 1)\right)$ with a break frequency at $\omega_R = 0.7$. However, the phase plot of the dynamic characteristics (Fig. 1) is quite different from that of a first order system. The phase angle (between the flow fluctuation and pressure rise fluctuation) decreases as the frequency increases until the break frequency; then it increases and reaches an asymptotic value of zero for large frequencies.

In the proposed transient analysis of the water tunnel circuit, various components of the circuit that influence the flow dynamics are modeled as point elements. As noted in the present Introduction, the transfer function for each element is then utilized in writing the boundary conditions for that element. Since the dynamic characteristics of the tunnel drive pump are available from the present analysis, the pump can be fully represented in such a transient analysis.

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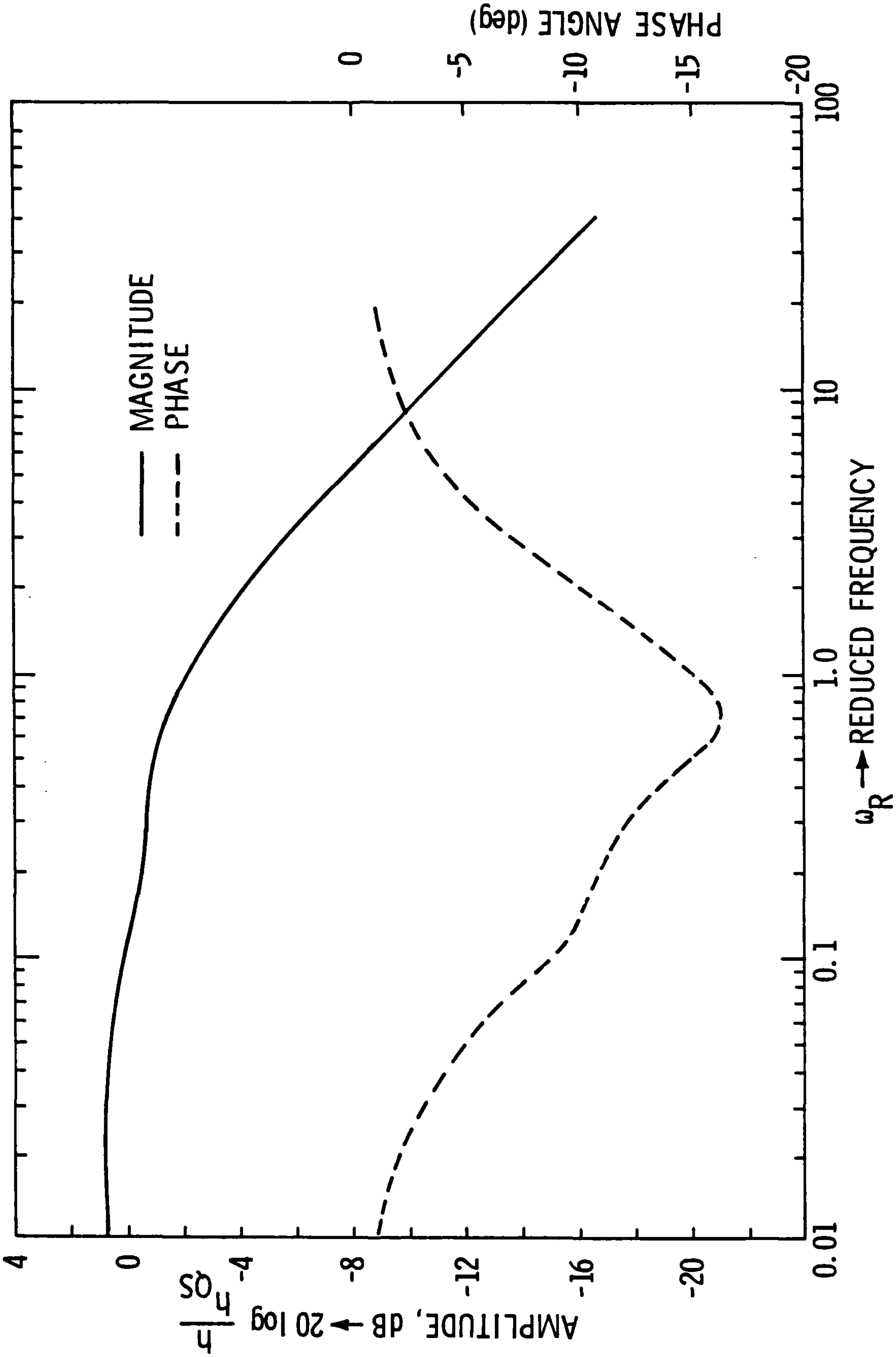

Figure 1. Dynamic Characteristics of 48-Inch Tunnel Drive Pump.

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